ESTIMATING SHIP TRAVEL TIMES ON INLAND WATERWAYS

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ABSTRACT

We present an innovative first-time adoption of two methods for estimating travel times of ships on inland waterways. These methods are based on historical data and currently observed velocities. Precondition for these methods is a tracking system for ships like the "Donau River Information Service" (DoRIS) as implemented in Austria. We therefore developed and tested the approaches on the Austrian part of the Danube. Numerical results indicate a clear improvement of the reliability of estimated arrival times of ships compared to state-of-the-art approaches based on average travel times of ships solely. Operators of locks and harbors benefit from the provided information because they can optimize their processes subsequent to the arrival of a ship.

INTRODUCTION

Recent studies (1) highlighted the importance of inland waterways for sustainably transporting goods. Beside the fact that waterway cargo is much more environmentally friendly than goods transported on roads, it often turns out that transportation on waterways is more reliable and even faster: While in Austria trucks are only allowed to be driven for 45% of a week (due to driving limitations), the Danube is on average available for 98.2% of the year (8). However, while there are several systems available for estimating the time of arrival of trucks at specific locations (e.g. 10), only a limited number of works exist focusing on the arrival time estimation of vessels. In this work we present novel methods for reliably estimating the speed of vessels on an inland waterway and computing the expected time of arrival at (inland) ports and locks.

The Danube is Europe's second longest river and an important inland waterway. People and goods are transferred between several harbors and berths along the river. The Austrian part of the Danube has a length of approximately 350 km. From the border to Slovakia to the border to Germany (upstream) it takes an average cargo ship about 45 hours to travel. In the opposite direction (downstream) this time reduces to 25 hours. On this part of the Danube a total of 11 Mio. t of cargo has been counted in 2010. This corresponds to an increase of 18.6% or 1.73 Mio. tin comparison to 2009. An advantage of waterway cargo is the possibility of transporting goods environmentally friendly while paying convenient prices. This is especially true for bulk freight. Moreover, the Danube is continuously available and not limited by periodically travelling prohibitions. From 1995 to 2010, the Danube was navigable (in Austria) for 98.2% of the year, i.e. on 359 days per year (8). Only during floodwater and the unlikely event of icing the concerned sections of the Danube are closed for shipping.

In contrast to cargo on road, capacity overloads and congestions are a minor problem since supply exceeds demand by far. This considers the waterway itself but not locks located along the river. On the Austrian part of the Danube there are nine hydropower plants with two parallel lock chambers at each site. Although several ships may pass the lock at a time (within one lock chamber), vessels have to frequently wait for service in front of locks due to high demand.

Although the current lock scheduling scheme applied follows a simple "first-come, first-serve" strategy, more elaborated strategies could be applied for improving the traffic flow on the river. For example, time slots could be assigned to each vessel indicating in which time slot the ship could pass the lock. Although the overall speed of ships is not increased by this locking strategy, dangerous situations arising due to space limitations can be reduced leading to an overall improvement of the (inland) waterway. Obviously, for finding an optimal schedule based on the assignment of time slots, it is necessary to reliably estimate for each vessel at which time it

will/could arrive at the locks. In addition, more dependencies between upstream and downstream ships have to be regarded such that waiting times in front of locks can be minimized. In return, the speeds of the vessels can be adapted such that the emission of greenhouse gases is reduced to a minimum.
In addition, the estimated time of arrival of (cargo) vessel at harbors can be used to pre-plan the deployment of human resources during loading and unloading of the transported freight. Since in most harbors landing stages are limited, quay times should be kept as low as possible. Furthermore, the estimated time of arrival can be used to pre-schedule subsequent transportation service (e.g. trucks).
So, to gain the desired benefit at locks and harbors, two crucial types information are necessary: On the one hand the current position of a ship needs to be known. On the other hand the most likely travel time of the ship until reaching its destination needs to be estimated. While the first (determination of location) is realized via river information services (RIS) systems as proposed by the RIS Framework Directive by the European Union (9) we are not aware of methods for reliably forecasting travel times of vessels.

STATE OF THE ART

Although the estimated time of arrival for vessels on inland waterways is of great importance when optimizing terminal operations and other resource constrained activities, there exists only a rather low number of works focusing on this topic. All works and services to be found in the literature are primarily based on the computation of average speeds. However, influencing factors like mean draught, current loading as well as the current vessel compilation are currently neglected.
Most importantly (since practically available), a travel time estimator for the Danube (6)is already provided by the “via donau” an enterprise responsible for maintenance and development of the Danube as inland waterway. Dependent on the origin, the destination and the type of vessel, a travel time is estimated. However this approach is based on several assumptions: The state of charge (in tons) is mostly unknown and therefore an average value is used for estimating. Very often a tow ship and one or several lighters are connected to a pushing unit. The current compilation of the pushing unit and the barges/lighters is not respected. Further it is assumed that the ship is propelled at maximal power although it falls to the captain at which speed he travels. Therefore, the travel time will most likely substantially deviate from the estimated average.
In addition, there are several studies dealing on methods and tools building upon estimated vessel speeds. (Mean) velocities for these methods stem from different data sources and/or assumptions. E.g., the European Conference of Ministers of Transport indicated in (1) a cruising speed of inland navigation vessels in the range of ten to twelve km/h. An example of a method using average vessel speeds can be found in a report of Klein et al (3), describing methodologies that are used to calculate the emissions of ships on inland waterways. The calculation is based on recorded speeds of 28 different vessel, various inland waterway types and rivers. Moreover a distinction has been made only between fully loaded and totally unloaded ships.
Almaz and Altiok (4) developed a simulation model to study issues regarding the Delaware River’s (US) operation via scenario analysis such as increase in vessel arrival, deepening the River and changes in the operational/navigational policies. Input data for the model were among others estimated vessel travel times between all possible origin-destination pairs and are

calculated based on predefined probability distributions specific to vessel types. Therefore historic travel times between different origin-destination pairs were recorded.
A model for managing the transit vessel traffic in the strait of Istanbul has been developed by Ulusçu et al (5). This model implements a scheduling process and is validated by comparing its results with scheduling decisions made by the operators. Again travel times or speed of ships are a prerequisite for applying the model and are assumed at a constant value of 10 knots (18.52 km/h), which is the speed limit in the strait of Istanbul.
The studies available primarily rely on average speeds (for vessel types and filling levels), however, a set of factors influence the (maximum) speed of a ship: In (7), Sun investigated the energy efficiency of ships on inland waterways. In his study he listed several factors increasing the energy consumption, while maintaining a certain travel speed. Conversely his results may be used to estimate a travel speed while assuming a constant engine power. These factors were current flow velocity, waves, water resistance, wind resistance and friction resistance caused by the surface roughness of the ship's hull: In contrast to landside transportation routes, an inland waterway is flowing. The ship has to overcome or may travel with the current flow velocity, which decreases the ship's travel velocity upstream. The current flow velocity is varying in space and time but is in general only measured at specific locations (such as locks and landing stages) but not between them. Larger waves are created in shallow water increasing water pressure on a ships movement and extra resistance is produced. This effect depends on the ships dimension, type and speed. A main factor for decreased travel speed (or increased power consumption) is water resistance which depends on the square footage of the front and properties of the water. Moreover the effective square footage of the front depends on the forward draft of the ship which is varying with the filling level. It has to be mentioned, that the relation between speed and energy consumption due to water resistance is cubical, meaning that double speed results in eightfold water resistance related energy consumption (11). Reductions in travel speeds of ships due to wind resistance are considerable for ships with large lateral areas above water level. Surface roughness of a ship hull is not constant during its lifetime. A rough, unfouled hull surface can increase friction resistance up to 5%. Fouling can significantly increase this (7).
Finally, an applied approach for obtaining arrival times of ships is to ask the captain. However, this is only possible if there exists a communication channel for speech between harbor/lock and ship and there are no problems regarding the language. However it is still hard for the captain to estimate his arrival, especially if he is not travelling this waterway frequently. In addition, humans tend to under/overestimate travel times.
Although at a first glance strong relation to the estimation of travel times on roads exists, it has to be highlighted that road traffic has rather different characteristics: Travel times of road vehicles are determined by considering the relationship between demand (traffic density) and supply (speed limit, road capacity). Therefore methods consider the expected traffic demand for estimating future travel times (see e.g. 10). Since supply exceeds demand by far these methods are not applicable for shipping traffic. Normally road vehicles are equally constrained by the traffic situation and therefore experience almost same travel times (except for different speed limits and strongly abnormal driving behavior). Estimated road travel times always consider general vehicle classes like passenger cars or trucks. However ship travel times depend much more on individual factors and therefore a common travel time for all ships on a section cannot be estimated. Therefore it would be more reasonable to estimate individual ship travel times.
Although a strong influence of individual factors on ship travel times is indicated in the literature average travel times are estimated. Sometimes several ship classes are established in order to take into account such individual factors. In this paper individual travel times are estimated by

considering currently observed tracking data. An approach similar to this has not been found in literature.
The organization of the paper is as follows: In the next section the data base used for modeling is described. Then the developed methods are presented and afterwards two different applications and their reliability are described in a section. Finally the results are summarized and recommendations for further improvements are given in the conclusion section.

DATA BASE

In 2005, the European Union published the RIS Framework Directive (9) which regulates the application of river information services (RIS) on European inland waterways. Basically, this directive states that each ship has to be equipped with a transponder compatible with inland AIS (automatic identification system) which provides the current position of a ship via satellite-based radiolocation. In addition, information about the filling level, the origin, the destination and ship's status ((maximum) speed, type, etc.) are transmitted. This information is collected at a national service institute providing relevant data to other vessels and authorities (such as lock supervisors).Additional data (such as waterway maps, obstructions, operating state, water level, etc.) is provided and transmitted via RIS. In Austria, this directive was implemented by introducing DoRIS (Donau river information service) which is operated by via donau.
Along the Danube there exists an international accepted kilometrage beginning at the confluence into the black sea and is increasing upstream. The Austrian part of the Danube is located between km 1852 and km 2203. In this study the waterway has been segregated into sections limited by locks and/or national borders. In addition, one section has been split at the location of a harbor ("Ennshafen"), cf. Figure 1. Numbers between dots represent section IDs. Although a ship is not stopped at a lock, tollgate or similar within a section a constant velocity of a ship cannot be expected due to variations of the current along the river. Most of the recorded data (i.e. ship travel times) was acquired between section 10 and 17 in upstream direction. Please note, that only a sample of all track records was available. In Table 1, more details on the investigated sections and according number of observations are described. We need to highlight that since a "first-come, first-serve" strategy is applied at locks ships currently travel (in general) at maximum possible speeds which is a necessary prerequisite for the methods developed within this paper.

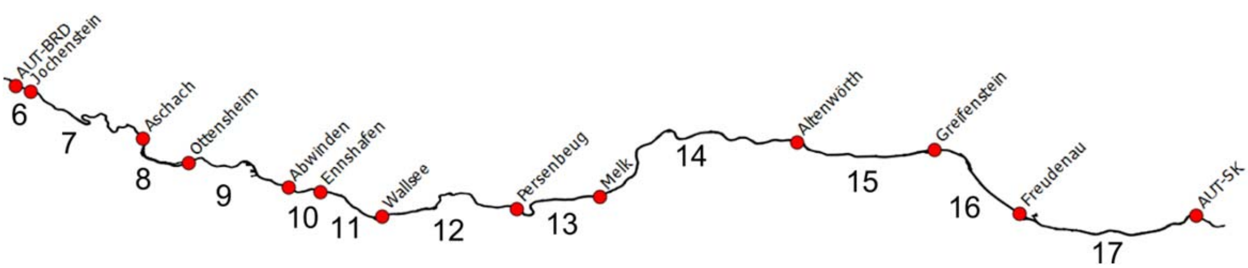

Figure 1: Location of hydropower plants and borders along the Austrian part of the Danube

Table 1: Summary of investigated sections and available ship data

Section ID	From	To	Length, km	Number of observations	Avg. Speed Upstream, km/h	Avg. Speed Downstream, km/h
17	AUT-SK	Freudenau	41	179	3.6	21.7
16	Freudenau	Greifenstein	28	102	7.1	16.6
15	Greifenstein	Altenwörth	31	165	9.1	17.7
14	Altenwörth	Melk	58	158	5.7	18.6
13	Melk	Persenbeug	22	176	8.4	17.1
12	Persenbeug	Wallsee	35	171	7.3	18.2
11	Wallsee	Ennshafen	16	185	9.8	16.5
10	Ennshafen	Abwinden	9	190	6.3	19.1

METHOD

In this section we describe a method for estimating ship travel times on an individual basis, i.e. ship travel times will be determined for each individual ship. First, from all track recordings those data have been removed, where a ship dwelled at a harbor. Travel time is estimated only for ships travelling directly between origin and destination. Operational stops at harbors cannot be considered, since no information about this stop is available (e.g. was the ship loaded/unloaded). Based on this pre-processing, it could be additionally ensured that the state of the ship in terms of state of charge and compilation of pushing unit is constant for the whole trip.
In the next step, track recordings were assigned to the sections and locks described above. Please note, that a lock itself is a region of about one to two kilometers. For this purpose, all GPS positions of a ship have been assigned to the corresponding section or lock. The travel time of a ship is then simply the time difference of the first and last position assigned to a section or lock. Please note, that for the sake of simplicity, the time required for passing a lock is also called travel time, although the ship is (most of the time) waiting inside and before the lock instead of travelling.
In the left plot of Figure 2an exemplary distribution of travel times for a selected section (upstream) is visualized. Additionally, the travel time distribution of ships passing the lock between section 12 and 11 (direction upstream) is presented in the right plot of Figure 2. Compared to the observed travel times for locks, the travel times at sections show a quite large variability, meaning that using an average travel time would lead to a rather inaccurate estimation.

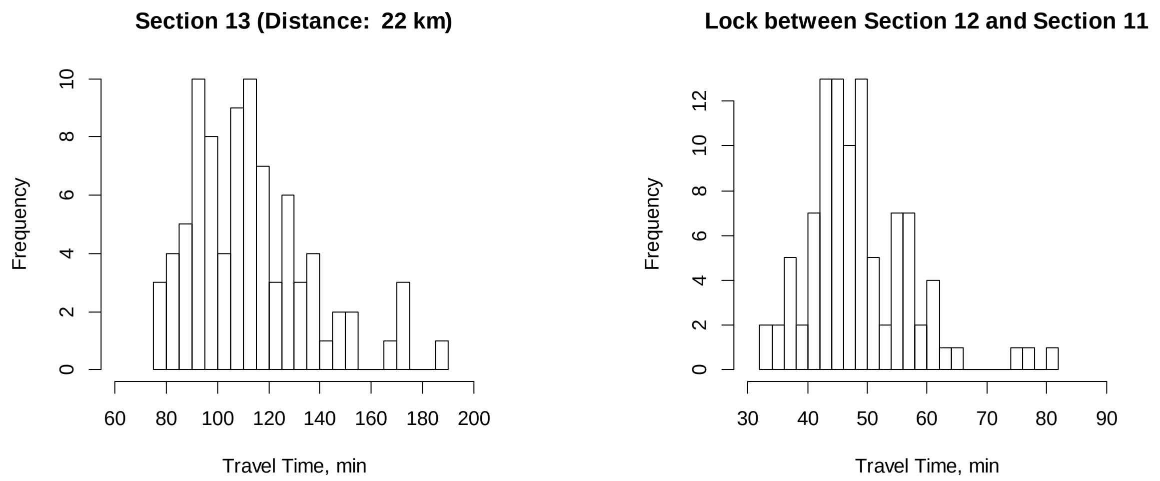

Figure 2: Histogram of ship travel times (left) at sections and locks (right)

The basic assumption of the method proposed in this work is, that expected travel times on next segments may be deduced from observed travel times on the last segments. I.e., if a ship is travelling slower on a section (compared to an average over all ships), then it will most likely travel slower on a subsequent section too. To underline this assumption, we show in Figure 3 exemplary plots of correlations of velocities of ships on three different sections. For the examined sections a good correlation is detectable since important properties influencing ship velocities (e.g. state of charge) are not changing during travelling. This is also confirmed by the high coefficient of correlation for all investigated pairs of sections listed in Table 2. In this table values in the lower left side represent correlation coefficients for sections pairs in direction upstream and for downstream in the upper right side. For missing values insufficient data have been available. Moreover a statistical test (t-test) indicated a significant correlation for all values of Table 2 (All p-values have been below 0.05), meaning that they are significant different to zero. However, this behavior could not be observed for service times at locks. A connection between travel times through different locks has not been found meaningful.

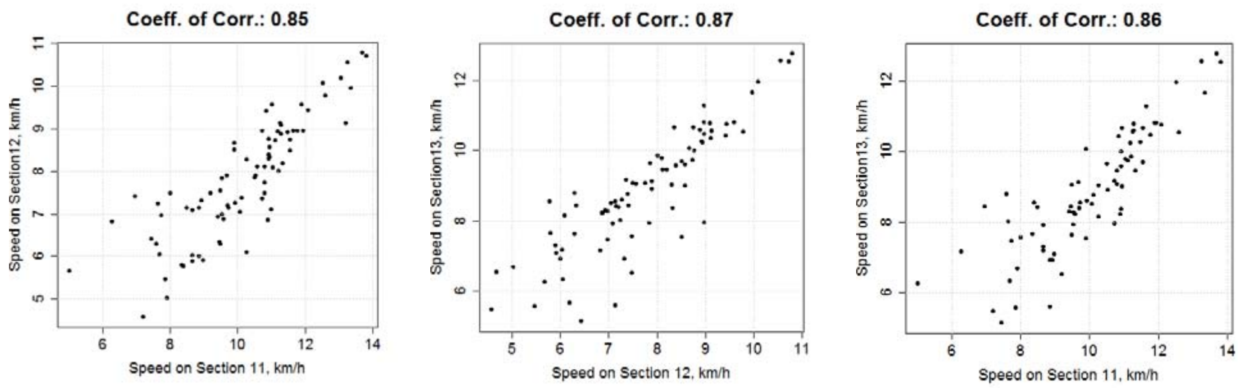

Figure 3: Correlation of travel times between three pairs of sections

Table 2: Correlation of travel speeds for different sections. Lower left side of matrix represents direction upstream and upper right side direction downstream.

To Section / From Section	10	11	12	13	14	15	16	17
10	1							
11	0.72	1						
12	0.8	0.85	1	0.79	0.86	0.8	0.71	0.74
13	0.75	0.86	0.87	1	0.77	0.71	0.51	0.56
14	0.82	0.72	0.86	0.81	1	0.69	0.68	0.51
15	0.71	0.87	0.82	0.88	0.78	1	0.67	0.74
16	0.68	0.68	0.75	0.8	0.74	0.84	1	0.82
17	0.68	0.62	0.73	0.66	0.92	0.64	0.76	1

Based on this observation, two methods have been developed. In order to compare these two new approaches with the state-of-the-art also a straightforward average travel time was estimated for sections (further called Method 1). Subsequent, all different methods are described, where Method 1 is rather elementary and does not rely on the assumption of correlated travel speeds:

- Method 1 – Average travel time for each section
  Based on recorded travel times on a section, an average value is estimated and assumed as travel time of a specific ship:

$$\tilde{t}_i = \bar{t}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} t_{i,j} \qquad (1)$$

  where
  $\tilde{t}_i$ … Estimated travel time on section i
  $\bar{t}_i$ … Arithmetic average of recorded travel times on section i
  $t_{i,j}$ … Recorded travel time of ship j on section i
  N_i … Number of observed travel times on section i

- Method 2 – Constant deviation in travel speed
  A constant deviation from an arithmetic mean speed over different sections is assumed. Therefore, first the deviation between average speed and observed speed on a section is determined and second this difference is subtracted from average speed of the current section:

$$\tilde{t}_i = \frac{L_i}{\bar{v}_i - (\bar{v}_{i-1} - \frac{L_{i-1}}{t_{i-1}})} \quad (2)$$

where
L_i … Length of section i
t_{i-1} … Travel time of ship for which estimation has to be performed on previous section
$\bar{v}_i$ … Arithmetic average of ship velocities on section i

- Method 3 – Variable deviation in travel speed
  This method is similar to Method 2 in terms of assuming continuing deviations in ship's speeds. The idea is to scale the deviation by a factor equal to the quotient of standard deviation at current and previous section. So if distribution of travel speeds in the previous section is large but small in the current section, a large deviation from a mean value in the previous section would be down-scaled to a lower deviation at the current section:

$$\tilde{t}_i = \frac{L_i}{\bar{v}_i - (\bar{v}_{i-1} - \frac{L_{i-1}}{t_{i-1}}) \cdot \frac{sd_i}{sd_{i-1}}} \quad (3)$$

where sd_i is the empirical standard deviation of speeds on section i.

For Method 1 no current ship velocities are required for estimating a travel time. However for Method 2 and 3 it is essential to know the travel speed on the previous section of the ship for which the estimation is performed. Further, the estimation has not to be based necessarily on travel times of sections back-to-back. E.g. if a travel time is predicted not for the current section but two or three sections ahead, also of the most recently completely travelled section travel speed is used. This means index i is replaced e.g. by i+1.
As mentioned above a good correlation only for travel speeds between sections could be observed. When estimating a travel time for a whole trip including several sections and locks, the travel time passing a lock is estimated by using an average value obtained from relevant historical data.

APPLICATION

In a first application the methods described above have been used for predicting the travel time of a ship on a single section. The prediction is performed at the moment the ship is entering the section. The time from leaving the lock at the beginning of the section and arriving the subsequent lock at the end of the section is estimated.
For the provider of the subsequent lock it is useful to know when the ship will arrive in order to be prepared (e.g. set proper water level in lock-chamber) and thus minimize waiting times. Moreover if arrival times of several ships are available, it is possible to concatenate two or three of them into one locking process if they arrive within a certain time span. Although the waiting time of the first ships would be increased, the overall waiting times of ships can be decreased. By

reducing the number of locking processes, less energy used for providing the lock is exhausted. Since each locking process decreases the amount of water flowing through the nearby located hydropower plant at the same site, a reduced number of locking processes will further increase the electricity produced.

In Figure 4 the relative absolute error of the estimated travel time is presented as boxplots. Upper and lower limit of the boxes represent inter quartile range, while whiskers at the end of dashed lines indicate the 2.5% and 97.5% percentile. Observations beyond whiskers are outliers (marked as circles). The median value of relative absolute errors is indicated by the horizontal bold line. The methods have been applied on real travel time observations of ships on different sections. Method 2 and 3 are based on travel speed deviation measured at the previous section. In the left plot of Figure 4 the estimation is based on information of the section immediately before. For the results visualized in the right plot of Figure 4, three additional sections were in between.

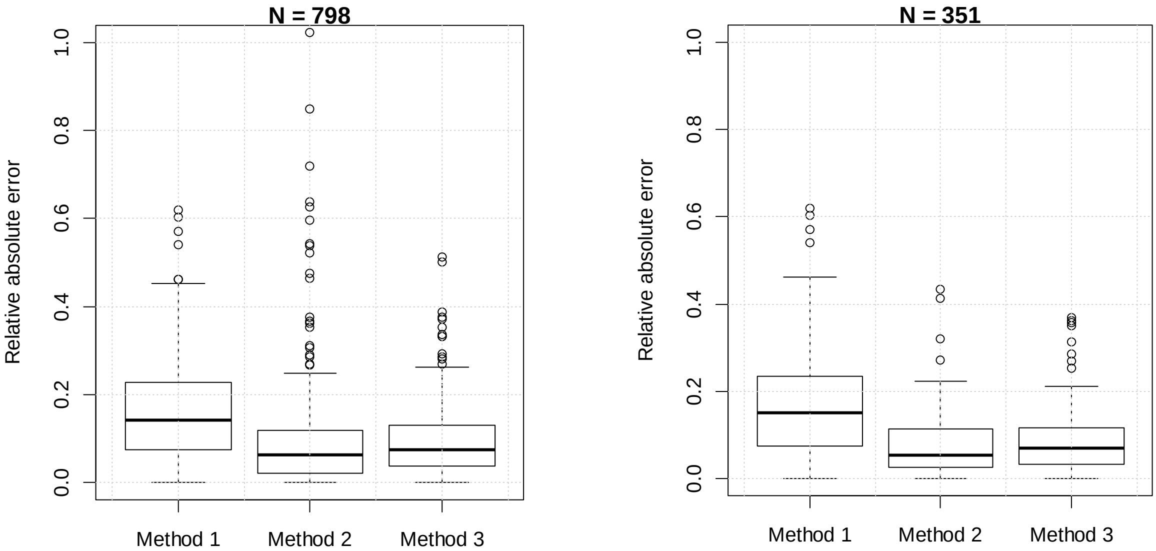

Figure 4: Relative error of travel time estimation based on information of adjacent section (left) and not adjacent section (right)

The boxplots in Figure 4 indicated that independent of the section on which travel speed difference was measured, a clear improvement of including this information (Method 2 and 3) compared to a simple average value (Method 1) is visible. The median values of relative error are listed in Table 3.

Table 3: Median values of relative error of estimated travel time

	Adjacent section	Non-adjacent section
Method 1	14.2%	14.2%
Method 2	6.2%	5.5%
Method 3	7.4%	6.9%

An improvement of Method 3 compared to Method 2 is not visible. Median value of error is even increasing although Method 3 is more complex. On the one hand, the standard deviation used for estimation is based on a limited number of observations and therefore contains a certain imprecision. On the other hand, estimated standard deviations are very similar between different sections resulting in almost same results for Method 2 and 3. I.e. quotient of standard deviations is close to 1 (cf. Eq. 3).

The second application for the developed methods was to estimate the travel time from a certain point to a specific location on the Danube. This target location always was a specific harbor (in our case “Ennshafen”), located between Section 10 and 11 (cf. Figure 1). As mentioned in the introduction the operators of the harbor could improve their performance when knowing the arrival time of a ship by allocating timely the required resources and landing stages and by adjusting subsequent transportation activities.

The methods have been tested for different scenarios based on real observations. First the trips of ships from the border to Slovakia (beginning of section 17) to the target location have been selected. For these trips the travel time was estimated several times, always when the ship entered a new section. E.g. when a ship entered section 16 the travel time to the harbor was estimated based on observed velocity on section 17. When it entered section 15, observed velocity on section 16 has been used for estimating and so forth. As mentioned above, estimating the travel time is not only possible for the directly next section but any subsequent one. This was necessary especially for this application, since the travel time for all further sections until the harbor had to be determined and accumulated.

The service time of each lock is determined by technical and operational specifications of the lock, and is approximately 45 minutes from registration to leaving the lock. This duration may change in dependence of the captain’s experience, attention, weather and illuminating conditions. Since no correlation could be observed between service times of different locks, a method similar to Method 2 or 3 has not been applied. Instead travel times for passing a lock between two sections has been estimated by using an average value of historical values.

In Figure 5, the average relative absolute error of travel times is visualized in dependence of the starting location. Additionally two times the confidence interval in both directions indicate the 95% range of errors. Again a clear improvement of the more sophisticated methods (Method 2 and 3) compared to the simple arithmetic average (Method 1) is visible. The relative error remains almost constant for varying starting location meaning that the absolute error decreases the closer the ship moves to the harbor. This is clearly visible from Figure 6, where the absolute error of travel time estimation is decreasing with decreasing remaining travel time to destination (end of section 11).

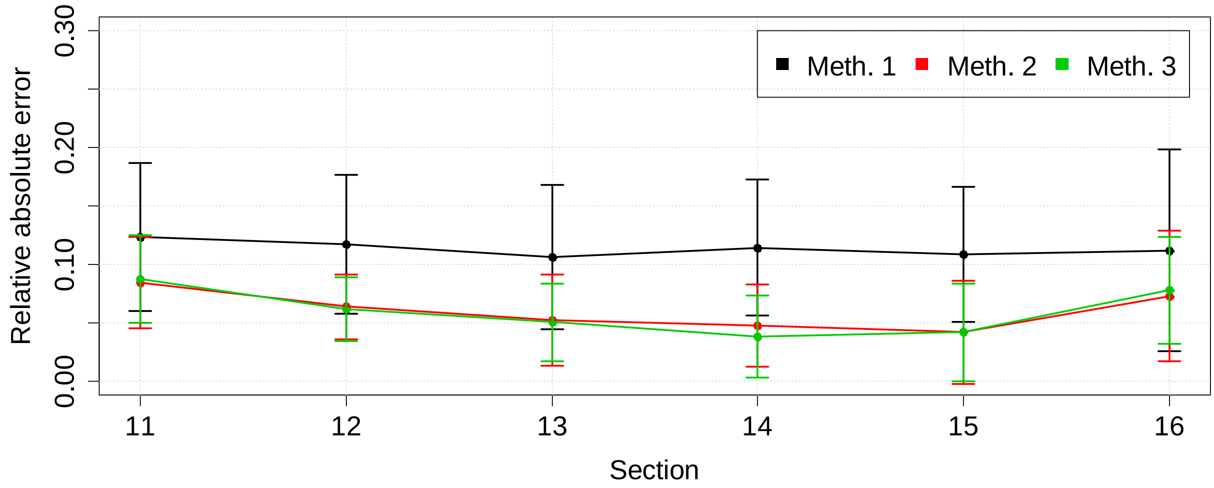

Figure 5: Relative error of estimated travel time in dependence of starting location. All ships were travelling to end of section 11.

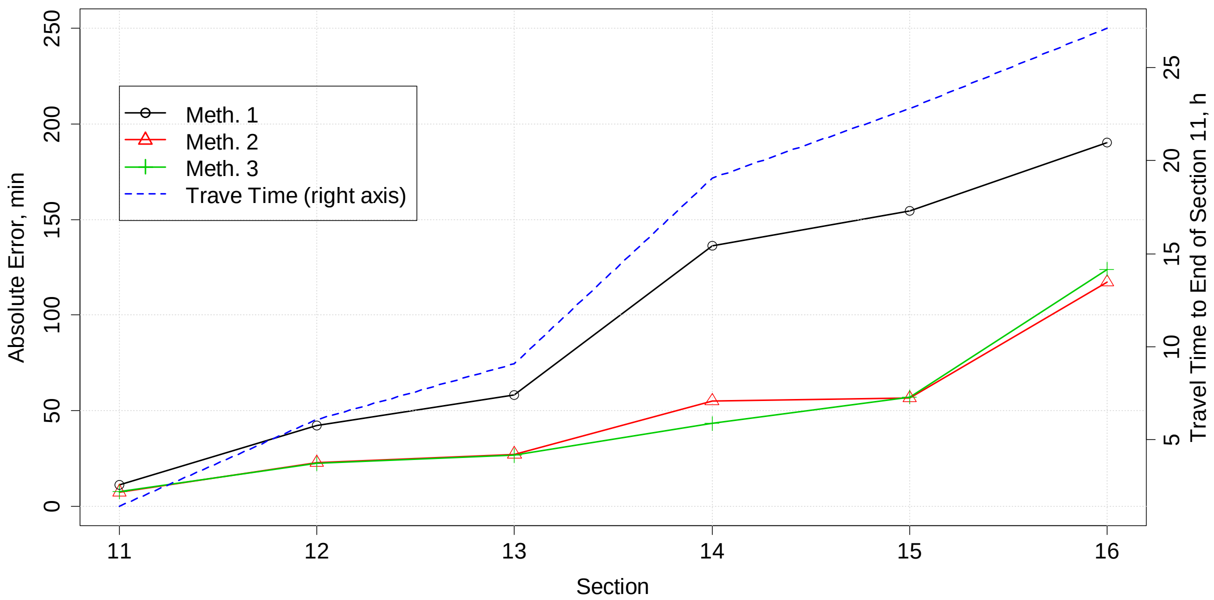

Figure 6: Absolute error of estimated travel time in dependence of starting location and average total travel time to end of section 11.

CONCLUSION

Two methods for estimating travel times of ships on inland waterways have been developed and applied on the Austrian part of the Danube. Basic assumption was that future travel times can be deduced from already observed ones. I.e., relatively slow ships will also travel at slow speed on subsequent sections and vice versa. A precondition for applying the methods is a tracking system for ships like DoRIS (Donau River Information Service). Since almost all countries located at the Danube already have or will implement a system similar to DoRIS (due to a directive of the European Union), results can be transferred to other parts of the Danube. Furthermore, we expect that these methods can also be applied to other important rivers in Europe (like the Rhine).

The first method (Method 2) assumes a constant deviation from an average travel speed obtained from historical data and the second one (Method 3) also considers the distribution of historic travel speeds. Estimated travel times have been compared to average travel times of ships, which was found in previous studies to be an accepted method. Results indicated a clear improvement in terms of relative absolute error of travel times for both developed methods compared to average travel times.

These results imply that operators of locks and harbors will benefit from an application of these methods due to pre-scheduling activities subsequent to the arrival of a ship. For the operators of locks the travel time was estimated for a specific section at the moment the ship enters this section. On the other hand travel times were estimated at any downstream location for the operator of a harbor, including several locks on the way. The extended time horizon for the harbor was necessary because activities subsequent to the arrival are more complex and require a long-term planning (e.g. allocating human resources) compared to activities at the lock. For estimating travel times of ships starting at any given location also travel times for passing locks have to be included. This has been done by estimating average service times of locks.

Estimating travel times by the methods developed in this study showed good results. However, for improving accuracy of longer trips also travel times for passing the locks have to be modeled instead of using an (arithmetic) average. This is a topic for future research activities, where service times at locks will be investigated in dependence of factors like demand, weather and illuminating conditions.

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